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Global trend in wind power with special focus on the top five wind power producing countries

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A B S T R A C T

Wind is one of the cleanest sources of renewable energy. The confidence on wind power can be realized from the recent growth of wind power at global level. Several countries have set specific target to meet substantial portion of their domestic energy demand from wind while many others have initiated large scale R&D. In this article, a comprehensive discussion on global trend in wind power is presented by highlighting potential, installation status and future prospect at global, regional and national context. A comparison on wind power status among the top five wind power producing countries viz. China, USA, Germany, Spain and India is also presented. The importance of use of modern tool and technique in wind power potential assessment is also discussed by highlighting wind power reassessment studies done for India.

Contents

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1. Introduction

Improvement in the quality and quantity of energy services particularly in the develpoing countries is the prime requirement to achieve the millenium development goals of the United Nations [1]. Realizing the need of universal access to energy, the United Nations has decleared the year 2012 as *The International Year of Sustainable Energy for All*. Renewable energy can contribute to social and economic development, energy access, energy security, energy independency and reducing negative impacts on environment and health. In fact, in many remote and inaccessible areas, locally available renewable resources are the only source of daily energy needs. In addition, renewable resources can provides excellent oppurtunity to substitute fossil energy use and thus to mitigate greenhouse gas emission and climate change [2,3]. In a recent report, the UN's intergovernmental panel on climate change (IPCC) has projected that renewable energy can provide approximately 77% of global primary energy supply by 2050. It is also projected that under different scenarios, deployment of renewable energy could reduce CO_2 emission from about 220 to 560 Gt between the year 2010 and 2050 compared to about 1530 Gt cumulative fossil and industrial CO_2 emissions in the same period under the reference scenario of the IEA's World Energy Outlook 2009 [4]. Deployment of 100% renewable energy system is also technically and economically feasible in the future [5]. The renewable energy policy network for the 21st century (REN21) has reported that renewable energy supplied 16% of global final energy consumption and delivered close to 20% of global electricity supply in 2010 [6]. It is projected that about 4.6 trillion kW h of renewable energy will be added to the grid during 2008–2035, out of which 27% will be contributed by wind alone [7]. Significant share of renewable energy in the total energy bugdet of several individual countries have also been noticed. For example, about 11% of domestic primary energy production in the US comes from renewables. In China, renewables accounts for 26% of total installed electricity capacity, 18% of generation and more than 9% of final energy consumption. Similarly, around 11% of total energy consumption in Germany comes from renewables [6]. In India also, renewable energy share more than 11% of total installed electricity capacity.

In terms of economy, global market share of renewable energy has also been growing fast. In 2005, solar, wind and biofuel together captured world renewable energy market worth of $39 billion (bn) which sharply increases to $246 bn in 2011 as shown in Fig. 1 [8]. Wind power alone shared $11.8 and $71.5 bn in 2005 and 2011, respectively. According to the European Wind Energy Association (EWEA), the European Union has installed wind power worth of $16.5 bn in 2011 [9].

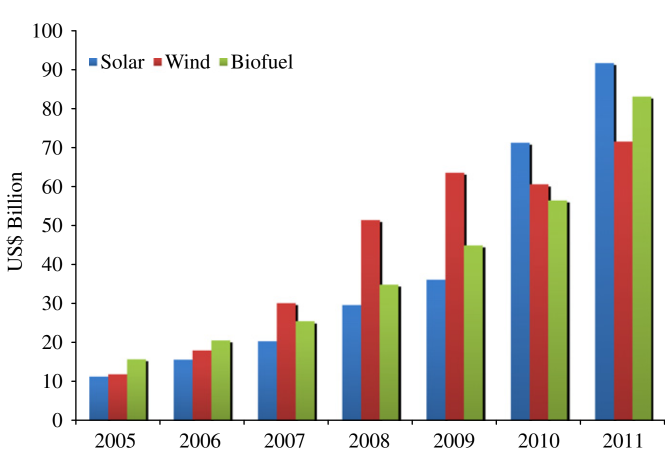

Fig. 1. Global investment in renewbale energy market.

Among all the renewables, wind is regarded as one the fastest growing renewable energy sector. The use of wind power has a long history, perhaps more than thousand years old (for example, use of wind energy for powering boats used on the Nile river) [10]. The interest on wind power has renewed after the mid 1973s oil crisis. Wind power is viewed as clean, practical, economical and environmental friendly alternative by society, industry and policy makers [11]. Wind power is locally available and it does not cause environmental pollution like acid rain, CO_2 emission or radioactive effect [10,12,13]. Because of the environmental benefits, public support for wind power project is often positive [14]. Generation of electricity from wind has more economic advantages than electricity generation from conventional fuels [15].

Over the last few years the world has witnessed significant development in the wind industry sector. A comprehensive discussion on the global status of wind power is presented in this paper. Wind power status in the top five wind power producing countries viz. China, USA, Germany, Spain and India is also presented highlighting potential, installed capacity, future prospect and regional or state level growth pattern. In case of India, wind power trend is more elaborately presented including a comparative study on the top five wind power producing states. Discussion on the reassessment of wind power potential studies done for India is also presented.

2. Wind power status: global, regional and national overview

2.1. Global overview

Studies have reported that global wind power potential is much higher than our present days' electricity consumption. According to Archer and Jacobson [16], global wind power potential was 72 TW in the year 2000. While estimating the potential, the authors have considered (i) only areas with high average wind speed of $\geq 6.9\ \mathrm{ms}^{-1}$, (ii) turbine size of 1.5 MW (iii) hub heights of 80 m and (iv) wind turbines capacity factor (CF) of 48%. The CF value is quite large, but it is applicable to areas with high wind speed ($\geq 6.9\ \mathrm{ms}^{-1}$). The estimated wind power potential have been found to be enough to produce over five times the global energy demand in all forms and about 40 times the global electricity demand of the year 2001. Even 20% of the potential (i.e., 14.4 TW) could be sufficient to mee almost all the global energy demand of the year 2009. Further areas with high wind power potential are distributed in the northern Europe along the North Sea, southern tip of the South American continent, the island of Tasmania in Australia, the Great Lakes region, and the northeastern and northwestern coasts of North America. However, Lu et al. [17], in a recent study reported that global wind power potential is 470 TW (equivalent to 2470 EJ on annual basis). This newly estimated potential is several times higher than the earlier figure of Archer and Jacobson [16]. While estimating the potential, Lu et al. [17] have considered (i) hub height of 100 m, (ii) turbine size of 2.5 MW for onshore areas, (iii) CF $\geq 20\%$. They further reported that larger GHG emmiters like Russia, China, USA, India and Canada, each of them have enormous onshore wind power potential greater than 1000 GW. In fact, Russia alone have 82,000 GW of onshore wind power potential. Its offshore potential is also very large, over 15,000 GW. However, it would not be feasible to exploit 100% potential because of geographical constraints and other limiting factors. Global distribution of annual average onshore wind power potential as reported by Lu et al. [17] is shown in Fig. 2.

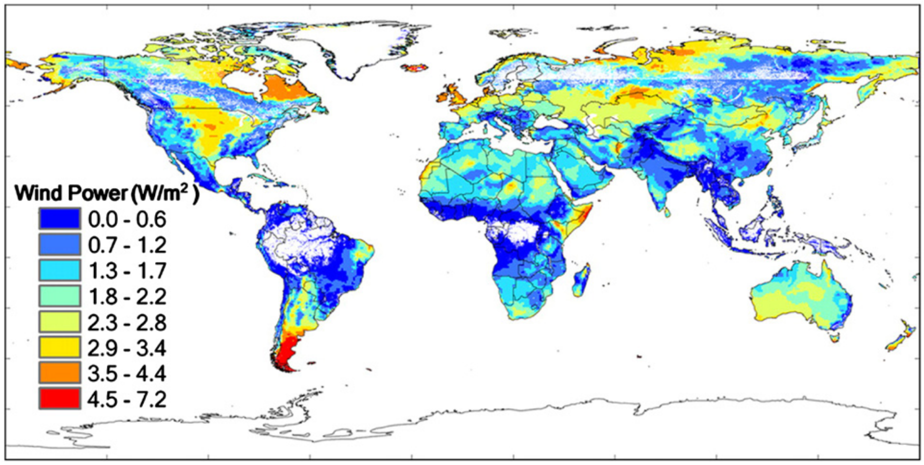

Fig. 2. Global distribution of annual average onshore wind power potential (Wm^{-2}) (taken with permission from [17]).

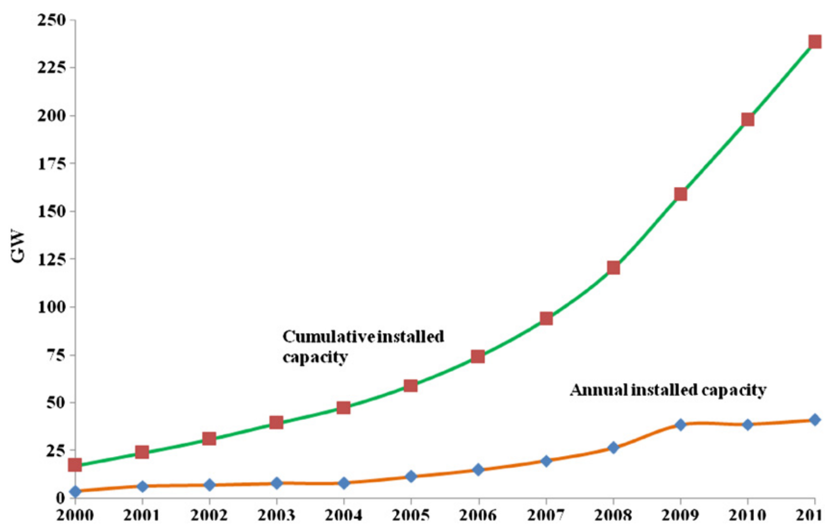

Fig. 3. Global trend in wind power installation during 2000–2011.

In the last few decades the world has witnessed tremendous growth in wind industry sector. Today wind represents 36% of total renewable energy generated worldwide. By the end of 2011, globally more than 238 GW wind power is installed, 14 times greater than the cumulative installed capacity of the year 2000 as shown in Fig. 3. Almost 70% of the global capacity is added alone in the last 5 years (2007–2011). Globally 41.24 GW of new wind power is installed alone in 2011. The World Wind Energy Association (WWEA) has projected that by the year 2015 and 2020, global wind power capacity will increase up to 600 and 1500 GW, respectively [18].

2.2. Regional overview

In the regional context, Europe has installed the highest amount of wind power (96.7 GW) followed by Asia (82.4 GW) and North America (52.18 GW) by the end of 2011. Annual wind power capacity addition at regional level in the last five years (2007–2011) is shown in Fig. 4. In terms of new capacity addition alone in 2011, Asia tops with new addition of 21.3 GW while Europe and North America has added 10.3 and 8 GW, respectively. In fact, Asia leads in annual capacity addition consecutively for last three years (2009–2011) as seen from Fig. 4. The impressive growth in Asia is mainly due to the unprecedented progress in the wind industry sector of China and India. On the other hand, progress in wind power sector is relatively slow in other regions of the World. For example, cumulative installed capacity in the Latin America & Caribbean region is only 3.2 GW as of 2011. Similarly, till 2011 Pacific region and Africa & Middle East have total installed capacities of only 2.86 and 1.1 GW, respectively [19].

2.3. National overview

Till 2011, 83 countries have installed wind power on commercial basis and 22 countries have reached cumulative installation capacity over 1 GW. At present China, USA, Germany, Spain and India are the world's top five wind power producing countries. Together they share 74% of global installed capacity. Of the global wind power addition of 41.24 GW in 2011, China, USA, Germany, Spain and India contributed 18 GW, 6.8 GW, 2 GW, 1 GW and 3 GW, respectively. Detail discussion on wind power status in these top five countries are presented later in this paper. Geographical distribution of the countries which have installed wind power projects is shown in Fig. 5.

In the following Sections 2.3.1 to 2.3.6, wind power status in some selected countries of the above discussed regions (Section 2.2) is briefly mentioned.

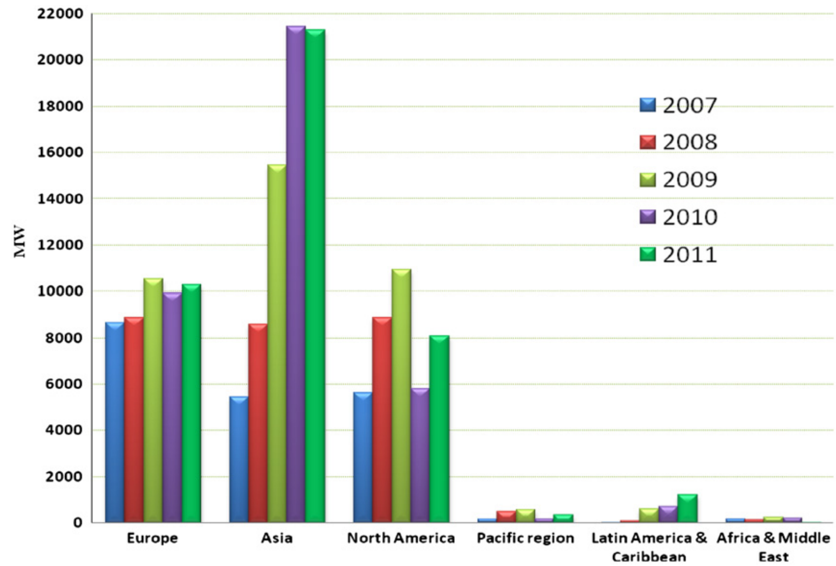

Fig. 4. Regional growth in annual wind power installation during 2007–2011.

2.3.1. *European countries*

As of 2011 the top five wind power producing countries in the Europe are Germany (29.06 GW), Spain (21.67 GW), France (6.8 GW), Italy (6.73 GW), and UK (6.54 GW). Together they share about 73% of Europe's installed capacity. Other European countries which have achieved installed capacity over 1 GW by 2011 include Portugal (4.08 GW), Denmark (3.87 GW), Sweden (2.97 GW), Netherlands (2.32 GW), Turkey (1.8 GW), Ireland (1.63 GW), Greece (1.63 GW), Poland (1.62 GW), Austria (1.08 GW) and Belgium (1.07 GW). Overall, wind power installed by the end of 2011 would, in a normal windy year produce about 204 TW h of electricity in European Union, representing 6.3% of the EU's total electricity consumption [9].

2.3.2. *Asian countries*

In Asia, both China and India have established themselves as global leaders in wind industry sector. Together they share nearly 96% of Asia's installed capacity. Wind industry development in Japan is also encouraging. By the end of 2011, Japan has installed 2.5 GW wind power which is the 3rd largest in Asia. Most of the wind resources in Japan are distributed in the Hokkaido, Tohoku, and Kyushu regions [20]. Further, on long term prospective, Japan has planned to develop 50 GW wind power by 2050 in order to supply more than 10% of country's total power demand. Other growing wind markets in Asia include Taiwan (0.56 GW), South Korea (0.4 GW) and Vietnam (0.03 GW). However, progress in countries like Bangladesh, Indonesia, Philippines, Sri Lanka and Thailand is slow [19].

2.3.3. *North American countries*

In the North American region, USA has the highest installed capacity of 47 GW followed by Canada (5.27 GW) and Mexico (0.57 GW). Detail discussion on wind power status in the US is presented later. Canada has been giving serious attention in wind industry. The country has added 1.27 GW wind power alone in 2011. Several new wind power projects were also commissioned in British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, New Brunswick, and Nova Scotia regions [19]. Currently Ontario is the leading provincial region in Canada in terms of installed capacity followed by Quebec and Alberta. Canada has planned to generate 20% of its electricity requirement from wind by 2025 under its ambitious plan 'WindVision 2025' [21]. This will necessitate development of 55 GW wind power by 2025, putting thousands of wind turbines over hundreds of locations of the country. Mexico has been also developing its wind sector. Wind power potential in the country at capacity factor above 20%, 25% and 35% are reported to be about 71, 30 and 21 GW, respectively [19]. Many regions of the country are rich in wind resources, particularly the Isthmus of Tehuantepec. Other important areas include La Rumorosa, northern coast on the Gulf of Mexico, Bay of Campeche, Yucatán Peninsula and the northern and central regions of Mexico in the states of Nuevo León, Coahuila, Chihuahua and Sonora [22].

2.3.4. *Pacific countries*

In the Pacific region, Australia has the highest installed capacity of 2.2 GW followed by New Zealand (0.62 GW). Australia share almost 78% of Pacific region's installed capacity [19]. Wind power share about 2.4% of Australia's total energy consumption on annual basis. Till March 2012, total number of wind turbines installed in the country is 1345, of which highest numbers are installed in South Australia followed by Victoria, Western Australia, New South Wales, Tasmania and Queensland. Australia has proposed to install another 15 GW, of which major capacity addition will be occurred in New South Wales and Victoria followed by Queensland, South Australia, Australia and Tasmania [23]. In New Zealand wind power supplies about 4% of annual electricity generation. Wind farms in the country are located in the areas like Palmerston North, Lower Hut, Wellington, Christchurch, Dunedin etc. The country has planned to develop 3.5 GW wind power by 2030 to supply 20% of New Zealand's electricity demand [24].

2.3.5. *Latin American & Caribbean countries*

Latin America & Caribbean region have large potential for wind power development, but only Brazil has crossed the milestone of 1 GW installed capacity till 2011 [19]. Brazil alone share about 65% of installed capacity of the entire Latin America & Caribbean region. Almost 63% of Brazil's total installed capacity is added alone in 2011. The best proven wind resources in the country are distributed in the states of Rio Grande do Norte, Ceará, Pernambuco and Bahia. The Brazilian Government's scheme '*Program of Incentives for Alternative Electricity Sources (PROINFA)*' is instrumental in the progress of renewable energy utilization. Argentina has been also developing its wind industry sector and its total installed capacity reached up to 130 MW in 2011. The Patagonia region of the country has one of the best wind characteristic in the world with meteorological wind

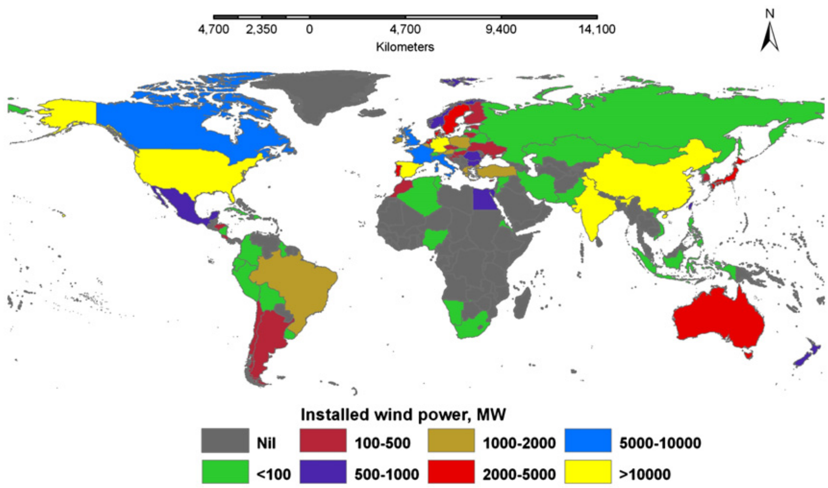

Fig. 5. Geographical distribution of the countries which have installed wind power projects (Installed capacity up to 2011: less than 100 MW in 40 countries, 100–500 MW in 14 countries, 500–1000 MW in 7 countries, 1000–2000 MW in 7 countries, 2000–5000 MW in 6 countries, 5000–10000 MW in 4 countries and above 10,000 MW in 5 countries; data collected from Global Wind Energy Council, European Wind Energy Association, and World Wind Energy Association).

power potential of 200 GW [25]. Other Latin American countries which have installed wind power over 100 MW include Chile, Costa Rica and Honduras. Concerning the Caribbean countries, wind energy could provide more than 10% of electricity consumption in many countries [26]. Examples of Caribbean countries which have installed wind turbines include Jamaica, Cuba, Dominica, Guadalupe, Curacao, Aruba and Bonaire.

2.3.6. African countries

In Africa, the best windy locations are distributed in the coastal and eastern highlands. However, only Egypt, Morocco, and Tunisia have installed wind farms on commercial scale. Together they contribute 95% to Africa's installed capacity. With 550 MW of total installation by 2011, Egypt leads the wind industry sector of Africa. Wind resources in the country are promising along the Gulf of Suez, the west and east of the Nile valley and parts of Sinai [27]. On the other hand, areas which have potential for wind power in Morocco include Essaouira, Tangier and Tetouan, Tarfaya Laayoune, Dakhla, and Taza etc. [28]. Concerning other African countries, Ethiopia has brought its first wind farm in 2011. Similar progress is also expected in Nigeria and Mauritania by 2012 [29]. Kenya is all set to establish Africa's biggest wind farm in the desert around Lake Turkana. The proposed 300 MW farm would generate power equivalent to 20% of current installed electricity capacity of the country [30]. Similarly, South Africa has also planned to increase its wind power capacity from a meager 10 MW in 2011 to over 8 GW by 2030 [19].

It is observed that there is a variation in wind industry development among the nations. Overall, wind power installation in many European countries (Germany, Spain, France Italy, UK etc.) is impressive. In Asia, China and India are the growing leaders while in North America, USA and Canada are the major contributors. Wind industry development in many Latin American & Carribean and African nations yet to take pace despite having considerable potential. However, recent progress in countries like Brazil, Argentina, Eygpt, Morroco, Tunisia is encouraging.

3. Wind power availability indices in some selected countries

Installed wind power availability in some selected countries is also assessed in the present study concerning (i) per capita population and (ii) per sq km land area. For this purpose, countries which have reached wind power installation capacity atleast 1 GW by 2011 are selected (total of 22 countries). Country wise population and land surface area data pertaining to the year 2010 are taken from the World Bank database [31]. While estimating wind power availability per sq km of land, only the land surface areas of a nation are considered. The results are presented below.

3.1. Per capita wind power availability

Our analysis indicates that Denmark has the highest per capita installed wind power (0.70 kW $capita^{-1}$) followed by Spain (0.469 kW $capita^{-1}$) and Portugal (0.379 kW $capita^{-1}$). The lowest per capita installed wind power availability is observed in Brazil (0.008 kW $capita^{-1}$). Although China, USA and India are the three leading wind power generating countries, their per capita wind power availability are only 0.047, 0.15 and 0.013 kW, respectively. Per capita installed wind power availability in the selected 22 countries is presented in Fig. 6.

3.2. Per sq km wind power availability

While plotting the cumulative installed wind power against the land surface area for each of the selected 22 countries, it is observed that per sq km installed wind power availability is the highest in Denmark (91.23 kW) followed by Germany (83.36 kW) and the Netherlands (48.35 kW). For other European countries such as Portugal, Spain, Belgium, UK, Italy, Poland, Austria, Greece, France and Sweden the value is 44.64, 43.45, 35.60, 27.03, 22.94, 19.60, 13.11, 12.64, 12.42 and 7.24 kW per sq km, respectively. Availabilities in China, USA and India are 6.73, 5.13 and 5.41 kW per sq km, respectively. On the other hand, less than 1 kW wind power per sq km of land surface is observed in case of Brazil, Canada and Australia.

As mentioned earlier China, USA, Germany, Spain and India are the top five wind power producing countries in the world. In the following sections, wind power status in these countries is discussed in detail.

4. Wind power status in the world's top five wind power producing countries

As of 2011 China, USA, Germany, Spain and India are the world's top five countries in terms of cumulative installed wind power capacity. China has added 18 GW alone in 2011 (44% of global new addition), followed by USA (6.8 GW), India (3 GW),

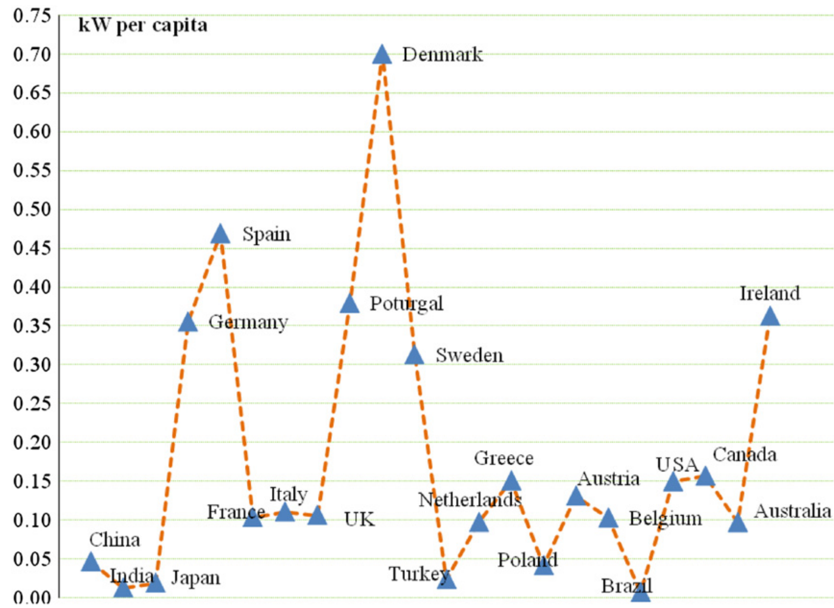

Fig. 6. Per capita installed wind power availability in some selected countries.

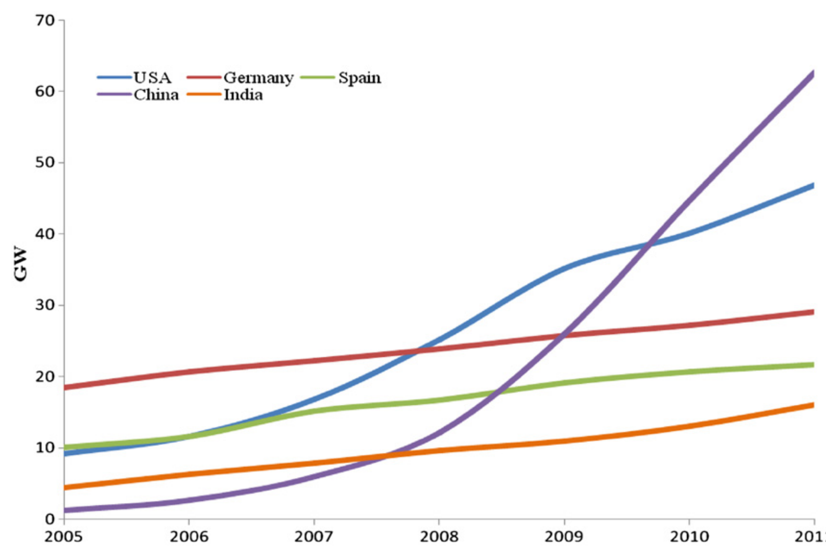

Fig. 7. Growth in wind power installation in the world's top five countries during 2005–2011.

Germany (2 GW) and Spain (1 GW). In fact, China's new installation is 40% higher than the aggregate installation of the remaining four countries. Annual wind power growth from 2005 to 2011 in these top five countries is shown in Fig. 7. Until 2007, Germany was the leading country in wind power installation whereas China was placed in last position as seen in Fig. 7. However from 2007 onwards both USA and China has exponentially increased installation capacity whereas progress in the remaining three countries was slow (Fig. 7). As a result, USA has surpassed Germany in 2008 and became the global leader in wind industry. On the other hand, during the period of 2006 to 2010, each year China has achieved more than 100% annual growth rate, which helped the country to become global leader in wind power in 2010 by surpassing USA.

4.1. Wind power status in China

In 2009, the Chinese Government has made a public commitment at the Copenhagen Conference on Climate Change that it would increase renewable energy generation to meet 15% of the country's energy demand by 2020. To fulfill this commitment China has planned unprecedented boost in the renewable energy sector including wind. The potential for exploitation of wind power in China is enormous. The China Meteorological Administration (CMA) has conducted nationwide investivation (the 4th National Wind Resource Investigation since 2007) to assess wind power potential in the country using wind data from wind towers and computer assited GIS based numerical simulation. The study found that technically exploitable onshore (land-based) wind power potential varies from 800 to 2900 GW at 50 m height, 1000 to 3600 GW at 70 m height and 1500 to 4000 GW at 100 m height [32]. China has vast land mass and long coast line favorable for wind power trapping. Wind power resources in China are particularly abundant in the southeast coastal regions, the islands of the coast and in the northern part (northeast, north and northwest) including some places in the inland regions. Coastal areas such as Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi and Hainan are rich in wind resource with

annual wind power density above 200 $\mathrm{Wm^{-2}}$. The zones with rich wind power potential in the north includes 200 km wide zones in the three northeast provinces of Hebei, Inner Mongolia, Gansu, Ningxia and Xinjiang, where wind power density reaches over 200–300 $\mathrm{Wm^{-2}}$ and sometimes more than 500 $\mathrm{Wm^{-2}}$ [33].

In case of offshore wind power, the reported potential in China is about 500 GW in areas with water depths between 5 and 50 m [32]. The Taiwan Strait area has the most potential for offshore wind power followed by Fujian, southern Zhejiang, Guangdong and Guangxi. Till 2011, China has exploited over 258 MW offshore wind power, third largest in the world only after UK and Denmark [34]. About 108 MW have been alone installed in 2011 of which 99.3 MW through the Jiangsu Rudong demonstration project. The Chinese Government has targeted to install 5 GW offshore wind power by 2015 and 30 GW by 2020.

Among the provincial regions, the Inner Mongolia province with more than 17.5 GW installed capacity is the leading province in China followed by Hebei (6.9 GW) and Gansu (5.4 GW). The top ten Chinese provinces in terms of cumulative installed capacity are given in Table 1. Provincial wind power installed capacity data are taken from Global Wind Energy Council (GWEC) [19]. Considering the capacity addition alone in 2011, the highest installation is observed in Inner Mongolia (over 3.7 GW), followed by Hebei (about 2.17 GW) and Shandong (over 1.9 GW) as shown in Table 1. However, the highest annual growth during 2010–2011 is observed in Ningxia and the lowest in Gansu province.

Per capita and per sq km (all land included) wind power availability in the Chinese provinces are also assessed and presented in Table 1. The highest per capita availability of 0.71 kW is observed in Inner Mongolia province while the lowest is in Shandong province (0.05 kW per capita). On land area basis, the highest availability is observed in Ningxia (43.73 kW per sq km) and the lowest in Xinjiang (1.45 kW per sq km).

Some of the largest wind power developers of China such as Guodian (Longyuan Electric Group), Datang, Huaneng, Huadian and China Guangdong Nuclear Power have been actively involved in the wind power sector of China. For example, Guodian has installed over 5 GW wind power followed by Datang (4 GW) and Huaneng (3 GW). Further in 2011, four wind turbine manufacturing companies of China namely Goldwind, Sinovel, United Power and Mingyang were listed in the world's top ten wind turbine manufacturers. Together they shared about 27% of global installation in 2011.

However, one of the major obstacles in the future growth of wind power in China is the imbalance between geographical distribution of wind power resource and electrical load [33]. The coastal areas of China have a large electrical load but are poor in wind power resource. On the other hand, wind power resource is plentiful in the north, but the electrical load is small. Further, many wind farms in China are remotely located from load centers. So the present grid connection system is not suitable for the development of wind power.

4.2. Wind power status in USA

Presently USA is the world's second largest wind power producer with total installed capacity of 47 GW (20% global share). The US wind industry has witnessed a fall in capacity addition in 2010 compared to 2009. However it has quickly recovered from such sliding and an increase in wind power instllation by 31% is observed in 2011 compared to 2010. Over 6.8 GW of wind power is added in 2011 in the US [35].

It is reported that wind power potentials in the US at 80 and 100 m height are 10,957 and 12,771 GW, respectively (with a capacity factor greater than 30%) [36]. This is much higher than previously estimated value of 8000 GW. About 26% land area of the entire US is available as windy land and most of the wind rich areas are located in the central regions, but many eastern and western states also have significant wind power potential. States that have more than 500 GW wind power potential at 80 m height include Texas (1902 GW), Kansas (952 GW), Montana (944 GW), Nebraska (918 GW), South Dakota (882 GW), North Dakota (770 GW), Iowa (571 GW), Oklahoma (517 GW) and Wyoming (552 GW).

To increase wind power,s contribution in the domestic electricity sector, the US Department of Energy has targeted 20% wind electricity generation, equivalent to 305 GW by 2030. It is expected that such plan would create thousands of jobs, increase annual property tax revenues and annual payments to rural landowners. Further the 20% wind electricity would displace 50% of electric utility natural gas consumption, reduce significant coal consumption and carbon dioxide emission [37].

Among all the US states, Texas has the highest installed capacity of 10.34 GW followed by Iowa (4.32 GW) and California (3.93 GW). In terms of installation alone in 2011, the highest installation is observed in California (0.92 GW), follwed by Illinois (0.69 GW) and Iowa (0.65 GW) [35]. The top ten states in terms of cumulative installed wind power capacity is shown in Table 2. In terms of per capita avaialbility of installed wind power, the highest availability is observed in North Dakota (2.15 kW per capita) and the lowest in Illinois (0.21 kW per capita). In case of per sq km installed wind power avaialbility, the highest is observed in Iowa (29.87 kW per sq km) and the lowest in Colorado (6.70 kW per sq km.) as shown in Table 2.

The immediate threat the US wind industry facing is the lack of stable and long term wind power policy. The Federal Production Tax Credit (PTC), one of the most crucial federal policies for wind power development, will be expired by the end of 2012. The PTC, introduced in 1992 has been playing a very important role in wind power development in the US. Equipped with the PTC, the

Table 1
Wind power statistics in the top ten wind power producing provinces of China.

Provinces	2010 cumulative (MW)	2011 new added (MW)	2011 cumulative (MW)	% annual growth	Installed wind power availability (kW per capita)	Installed wind power availability (kW per sq km)
Inner Mongolia	13,858.00	3,736.40	17,594.40	26.96	0.71	14.87
Hebei	4,794.00	2,175.50	6,969.50	45.38	0.10	36.68
Gansu	4,944.00	465.20	5,409.20	9.41	0.21	12.02
Liaoning	4,066.90	1,182.50	5,249.30	29.08	0.12	36.03
Shandong	2,637.80	1,924.50	4,562.30	72.96	0.05	29.82
Jilin	2,940.90	622.50	3,563.40	21.17	0.13	19.80
Heilongjiang	2,370.10	1,075.80	3,445.80	45.39	0.09	7.35
Ningxia	1,182.70	1,703.50	2,886.20	144.03	0.46	43.73
Xinjiang	1,363.60	952.50	2,316.10	69.85	0.11	1.45
Jiangsu	1,595.30	372.30	1,967.60	23.34	0.03	19.18

Table 2
Wind power statistics in the top ten wind power producing states of USA.

State	Available windy land area (sq km)	Potential [MW (80 m height)]	Installed in 2011 (MW)	Cumulative installation (MW)	Projects in queue (MW)	% share to state power in 2010	Installed wind power availability		Wind resource potential to replace current electricity needs
							kW capita^{-1}	kW sq. km^{-1}	
Texas	380,306	19,01,530	270	10,337	63,504	6.40	0.41	15.25	19 times
Iowa	114,143	570,714	647	4,322	14,569	15.40	1.42	29.87	44 times
California	6,822	34,100	921	3,927	18,269	3.30	0.11	9.72	39.40%
Illinois	49,976	249,882	692	2,743	16,284	2.20	0.21	19.05	525 times
Minnesota	97,854	489,271	542	2,733	20,010	9.70	0.52	13.25	25 times
Colorado	77,444	387,000	501	1,800	16,602	6.60	0.36	6.70	25 times
N Dakota	154,039	770,196	234	1,445	11,493	12.00	2.15	8.09	240 times
Oklahoma	103,364	516,822	525	2,007	14,677	5.10	0.54	11.28	31 times
Oregon	5,420	27,100	409	2,513	9,361	7.10	0.66	10.11	165%
Washington	3,696	18,479	367	2,573	5,831	4.60	0.38	14.93	64%

US wind industry has been able to lower the cost of wind power by more than 90%, provide power equivalent of 10 mn homes, foster economic development and earn billions of investment. The expiray of PTC may have serious consequences on the US wind power sector as evidence from historical events. For example, with the expiry of PTC in 1999, 2001 and 2003, a sharp drop of 93%, 73% and 77% in installation with corresponding job losses were observed in 2000, 2002 and 2004, respectively. Moreover, due to the threat of PTC's expiration, wind project developers are not making plans in the US and the American manufacturers are not receiving orders [38]. Thus, immediate extension of the PTC is crucial for overall development of the wind power industry in the US.

4.3. Wind power status in Germany

In the wake of Japan's Fukusima nuclear disaster in 2011, the German Government has announced an ambitous stratety to fully replace nuclear power with renewable energy by 2022. In her own words the German Chancellor Angela Merkel has expressed "We believe that we can show those countries who decide to abandon nuclear power – or not to start using it– how it is possible to achieve growth, creating jobs and economic prosperity while shifting the energy supply toward renewable energies". By switching over to renewable, the country is expecting a 40% reduction in CO_2 emission and doubling the share of renewable energy from 17% to 35% [39].

Germany is the European leader in wind power sector. With total installed capacity more than 29 GW, Germany's contribution to Europe's wind power sector is nearly 30%.

In 2011, about 2 GW of wind power is newly added, including 108 MW in offshore areas. Wind power generated 48 TW h of electricity in 2011, which accounted for 7.8% of the country's net electricity consumption [34]. In future wind power could provide up to 60% of Germany's current gross power generation if its potential is exploited to the full, both offshore and onshore [40]. The technical wind power potential with favorable wind speed is very good in Germany. In most of the region, the mean wind speed is 5 to 6 ms^{-1} on the coast and 4 to 5 ms^{-1} at favorable inland locations (50 m height). According to the German Wind power Association (BWE), the country could generate 45 and 10 GW onshore and offshore wind power respectively, by 2020. Further, installation of 20 to 25 GW offshore wind power by 2030 is also possible. The North and Baltic seas could play a key role in Germany's offshore wind power development. The North and Baltic seas are quite shallow and close to large urban areas and thus making them very suitable for offshore wind power.

In terms of wind power development among the federal states of Germany, the Lower Saxony state is leading with 7.039 GW installed capacity by 2011. It has also added 431 MW wind power alone in 2011, greater than any other states of Germany. The top ten wind power producing states of the country is presented in Table 3 (as of December 2011) [41]. Per capita installed wind power availability is the highest in Brandenburg and the lowest in Hessen. On the other hand, per sq km wind power availability is highest in Schleswig-Holstein and lowest in Hessen (Table 3).

However, the major obstacles facing by the developers in expanding wind power projects in Germany are (i) restriction in the hub heights in many regions has restricted the maximum generation of wind turbines and (ii) difficulty in underground cabling in some critical areas for speedy grid expansion. Another hurdle in case of offshore wind projects is the lack of infrastructure to transport generated electricity to the mainland power grid and delays in necessary connection and cabling.

4.4. Wind power status in Spain

Wind power is the third largest source of electricity in Spain after natural gas and nuclear. Spain has recovered almost 16% of energy demand using wind power in 2011. Fueyo et al. [42] reported that the overall technical wind power potential in Spain is approximately 1100 TW h yr^{-1} and that about 70 GW of installed wind power could operate with capacity factors in excess of 24%, resulting in an annual electricity generation of approximately 190 TW h. The total installed wind power capacity in the country is about 22 GW by 2011. However, Spain's wind sector could installed only 1050 MW in 2011, representing an annual increase of 5.1% of accumulated power. This is the slowest growth in the history of wind power in Spain in percentage terms [43]. The Spanish Government has initially set a target to install 38 GW of wind power, 35 GW onshore and 3 GW offshore by 2020 in its National Renewable Energy Action Plan, but the later target for offshore wind power was lowered by 75% (from 3 GW to 750 MW), mainly due to economic crisis, growing deficit of power sector and the sluggish growth of power demand [34].

According to the Spanish Wind power Association (AEE), the Castilla y León region has the highest installation of wind power followed by Castilla-La Mancha and Galicia regions. Most of the wind farms in the Castilla y León region are distributed in the Soria, Palencia, Zamora and Burgos provinces. Similarly, in Castilla-La Mancha region, wind farms distributed in the Albacete, Cuenca and Guadalajara provinces [43]. The top ten regions of Spain in terms of installed wind power capacity are shown in

Table 3
Wind power statistics in the top ten wind power producing states of Germany.

State	Installation in 2011 (MW)	Cumulative installation (MW)	% share to state's net electricity consumption	Installed wind power availability (kW per capita)	Installed wind power availability (kW per sq km)
Lower Saxony	431	7,039	25.00	0.89	147.84
Brandenburg	181	4,601	47.70	1.84	156.06
Saxony-Anhalt	149	3,642	48.10	1.56	178.10
Schleswig-Holstein	300	3,271	46.50	1.15	207.04
North Rhine-Westphalia	160	3,071	3.90	0.17	90.08
Rheinland-Pfalz	258	1,663	9.40	0.42	83.76
Mecklenburg-Vorpommern	98	1,627	46.10	0.99	70.16
Saxony	33	976	8.00	0.24	52.99
Thuringia	49	801	12.00	0.36	49.53
Hessen	99	687	2.80	0.11	32.54

Table 4
Wind power statistics in the top ten wind power producing states of Spain.

State	Installation in 2011 (MW)	Cumulative installation (MW)	Installed wind power availability (kW per capita)	Installed wind power availability (kW per sq km)
Castilla y León	462.19	5,233	2.04	55.54
Castilla-La Mancha	26.5	3,737	1.78	47.03
Galicia	0	3,272	1.17	110.64
Andalucía	92	3,067	0.37	35.01
Aragón	50	1,811	1.34	37.96
Comunidad Valenciana	183	1,170	0.23	50.31
Cataluña	153.71	1,003	0.13	31.27
Navarra	8.5	977	1.53	94.02
La Rioja	0	428	1.33	84.92
Principado de Asturias	72.5	687	0.63	64.80

Table 4. It is observed that, except the Castilla y León, Comunidad Valenciana and Cataluña regions, wind power installation in other regions were not encouraging in 2011. Two of the top ten regions, Galicia and La Rioja have not installed wind turbine at all in 2011. In terms of per capita installed wind power availability, the highest availability is observed in Castilla y León and the lowest in Cataluña regions. On the other hand, Galicia region has the highest installed wind power capacity per sq km area while the Cataluña region has the lowest as shown in Table 4.

4.5. Wind power status in India

Wind in India is influenced by the strong south-west summer monsoon, which starts in May–June, when cool, humid air moves towards the land and the weaker north-east winter monsoon, which starts in October, when cool, dry sir moves towards the ocean. During the period march to August, the winds are uniformly strong over the whole Indian Peninsula, except the eastern peninsular coast. Wind speeds during the period November to March are relatively weak, though higher winds are available during a part of the period on the Tamil Nadu coastline [44].

The Centre for Wind Energy Technology (CWET) has estimated onshore wind power potential in India at 50 and 80 m height as 49 and 102 GW, respectively [45]. However, recent studies by different groups have reported that India's wind power potential is much higher than the CWET's estimated potential. This issue is discussed separately in the present paper. India's offshore wind power potential is yet to be systematically evaluated but it is reported to be about 20 GW [46]. The western coastline has the modest potential, while the Gujarat coastline has reasonable potential for offshore wind power. So far, two locations viz. Rameshwaram in Tamil Nadu and Mundra at Gulf of Kutch, have shown reasonable potential for offshore wind power.

The Global Wind Energy Council (GWEC) has projected the growth of wind power sector in India under three different scenarios viz. reference, moderate and advanced. Under reference scenario, wind power in India would be about 19, 24 and 30.5 GW, in moderate scenario it would be 25, 46 and 108 GW and in advanced scenario, it would be 29, 65 and 161 GW by 2015, 2020 and 2030, respectively [47].

As stated earlier, India ranks 5th in the world with over 16 GW installed capacity by 2011. From global point of view, India share 6.7% of wind power. India started its wind power programme during 1990s. However, wind industry growth in India has been sluggish and the country had to wait until 1998 to achieve 1 GW cumulative installation capacity. However from 2005 onwards, India's wind power sector has started growing fast with each year capacity addition of more than 1 GW. Historical growth pattern of India's wind sector is presented in Fig. 8.

India's wind resource is distributed in a few states only. For instance, Gujarat, Karnataka, Maharashtra, Andhra Pradesh, Tamil Nadu, Rajasthan and Jammu Kashmir, these seven states together share about 93% of India's wind power potential. As per CWET, all these states have been identified with wind power potential greater than 5 GW at 50 m height. In fact, wind power potential in Gujarat at 50 and 80 m height is more than 10 and 35 GW, respectively. In terms of installed capacity, these seven states together share almost 98% of wind power in India. State wise wind power potential and installed capacity along with per capita and per sq km availability is presented in Table 5.

Among the individual states, the highest per capita installed wind power availability is observed in Tamil Nadu and the lowest in Kerala (Table 5). Further, Tamil Nadu also has the highest wind power availability in terms of per sq km land area while Andhra Pradesh has the lowest (Table 5).

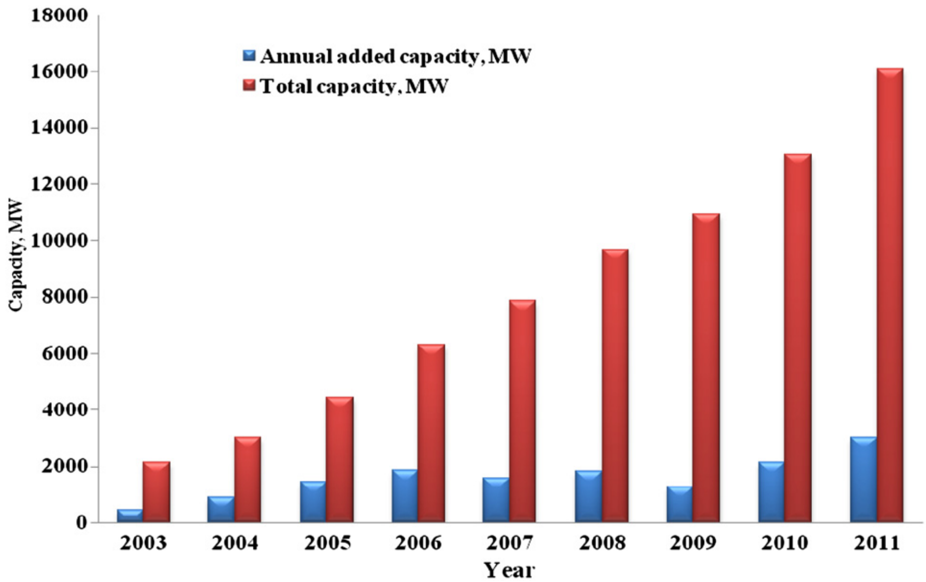

Fig. 8. Wind power growth in India during 2003–2011.

At present, Tamil Nadu, Gujarat, Maharashtra, Karnataka and Rajasthan are the top five wind power producing states in India. Together they share over 82% of India's wind power potential and more than 96% of installed capacity. A comparative analysis of wind power status among the top five states of India are presented below.

4.5.1. *A comparison of wind power status in the India's top five wind power producing states*

Wind power installation status over the last 10 years (2002–2011) in the top five states of India is presented in Fig. 9.

It is observed that the growth of wind power in Tamil Nadu has been far better than the remaining top four states of India. Tamil Nadu alone share 41% of installed wind power capacity in India [48]. However from last couple of years Maharashtra and Gujarat has been also increasing installation capacity very fast (Fig. 9).

Tamil Nadu has four prominent places with high wind potential. These are (i) Palghat Pass, Coimbator, Erode with annual wind speed between 18 and 22 km per hour, (ii) Shencottah Pass, Tiruneveli, Tuticorin with annual wind speed between 18 and 22 km per hour, (iii) Aralvoimozhi Pass, Kanyakumari with annual wind speed between 19 and 25 km per hour, (iv) Kambam Pass, Dindigul district with annual wind speed between 19 and 25 km per hour [49].

In Maharashtra, the wind farms are distributed in the Satara, Sangli, Anandnagar, Dhule, Thane, Nashik, Sindhudurga, Beed, Nandurbar, Amarawati and Pune districts. Most of the wind turbines are installed in the Satara district followed by Sangli. Mean annual wind speed in Satara and Sangli districts varies from 5.1 to 6.4 m s^{-1} and 5.5 to 6.3 m s^{-1}, respectively. As of March 2012, a total of 1456 turbines (out of the total 3184 wind turbines in Maharashtra) are installed in the Satara distrcits with cumulative capacity of 858.25 MW. Of this, 638 wind tubines are alone installed in Vankusavade site of the district [50].

In Karnataka, districts that have already comissioned wind power projects (as of March 2012) are Belgaum, Bellary, Chitradurga, Davanagere, Dharwad, Gadag, Haveri, Koppal, Raichur, Hassan, Shimoga and Tumkur. Among these, the highest capacity is installed in Chitradugra district (566 MW), followed by Gadag (422 MW), Davanagere (219 MW), Belgaum (193 MW) and Hassan (144 MW) districts. Recently, new locations with favorable wind speed for turbine instalaltion have been also identified in the Bijapur, Bidar, Bagalkot, Mysore, Kolar, Mandya, Chikkaballapura, Gulbarga, Yadgir districts etc.

Table 5
State wise wind power potential, installed capacity and availability indices in India.

State	Potential (MW)		Cumulative installation (MW)	Installed wind power availability	
	@ 50 m height	@ 80 m height		kW capita^{-1}	kW sq km^{-1}
Tamil Nadu	5,374	14,152	6,613.00	0.092	50.85
Gujarat	10,609	35,071	2,641.00	0.044	13.47
Maharashtra	5,439	5,961	2,560.00	0.023	8.32
Karnataka	8,591	13,593	1,852.00	0.030	9.66
Rajasthan	5,005	5,050	1,830.00	0.027	5.35
Madhya Pradesh	920	2,931	330.00	0.005	1.07
Andhra Pradesh	5,394	14,497	213.00	0.003	0.77
Kerala	790	837	35.10	0.001	0.90
Others	7,008	10,696	4.00	0.0000062	0.0025
Total (all India)	49,130	102,788	16,078.10	0.013	4.89

In Rajasthan, the highest number of wind power projects are commisoned in Jaisalmer district followed by Jodhpur. Against the installed capacity of 1208 and 289 MW in Jaisalmer and Jodhpur, respectively as of March 2011, installation in other parts of the state is very low, e.g., 12, 10 and 3 MW in Sikar, Barmer and Chittorgarh districts, respectively [51].

Gujarat with its longest coast line in the country and inland windy sites have huge potential for wind power development (over 10 GW). Altogether more than 65 sites have been monitored for the wind speed and wind power density in the states and over 50 sites have been found feasible for harnessing wind power [52]. Potential districts for wind farms development in Gujarat state includes Amreli, Bhavnagar, Dahod, Jamnagar, Junagarh, Kutch, Rajkut, Surendranagar and Porbander.

4.5.2. *Wind power potential reassessment in India*

The Center for Wind Energy Technology (CWET) is the nodal agency for coordinating wind resource assessment in India. As per

CWET, installable wind power potential in India at 50 m height is 49 GW, assuming 2% land availability for wind firm development for all the states except in the Himalayan states, Northeastern states and Andaman Nicobar Islands. In the later states, land availability is assumed as 0.5%. Similarly at 80 m height, wind power potential in India is estimated to be about 103 GW [45]. However, recently three different studies have reported that India's wind power potential is much higher than the estimated potential of CWET. A brief discussions on the three studies are presented below.

In a study on wind generated electricity potential at global scale, Lu et al. [17] reported that on annual basis onshore and offshore wind power potential (capacity factor $>20\%$ and hub heights 100 m) in India is 2900 TW h (1324 GW) and 1100 TW h (502 GW), respectively. This study was based on assimilation of wind data from varieties of meterological sources inclduing global wind field data from version 5 of the Goddard Earth Observing System Data Assimilation System (GEOS-5 DAS).

Hussain et al. [53] has assessed onshore wind power potential in India at 80 m height using GIS tools. They found that India's wind power potential is 4250 GW at PLF (plant load factor) categories ranging from 15 to 45% and if whole of the country (apart from urban and the Himalayan areas) is covered with windfarms. Further, even if PLF categories below 20% excluded and consider only the categories raning from 20 to 45%, the wind power potential would be still 2075 GW. They also mentioned that the overall wind power potential in India would be much higher if (i) the Himalayan region and North-Eastern states were also included, (ii) the assessment was done also at hub height of 100 m or even more which is suitable for wind turbines in the range of 2.5–7.0 MW operating in the European countries, and (iii) the offshore wind power potential was also estimated.

In an another study at Lawrence Berkeley National Laboratory, Phadke et al. [54] has recommended reassessment of India's wind power potential due to the following three reasons:

(i) Separate study conducted by Lu et al. [17] and Hussain et al. [53] has reported much higher wind power potential in India than earlier official estimation of CWET.
(ii) Reassessment conducted in USA and China have found much higher wind power potential than earlier estimation due to better technology in the form of higher efficiency, hub heights, and sizes of wind turbines.
(iii) GIS based systematic analysis provides precise estimation of land for wind power development. The potential estimated by the CWET assumes only 2% windy land availability for wind power development without proper explanation.

Considering these three issues, Phadke et al. [54] has reassessed India's onshore wind power potential at three different hub heights (80, 100 and 120 m) assuming turbine density of 9 MW $\mathrm{sqkm^{-1}}$ and a minimum capacity factor of 20%. They found that India's wind power potential ranges from 2006 GW at 80 m height to 3121 GW at 120 m height. This is nearly 20 times more than the estimation of CWET at 80 m hub height. The potential at high-quality wind power sites alone (80 m hub-height, WPD >250 W $\mathrm{m^{-2}}$ and CF $>25\%$) is 543 GW, more than five times larger than the current official estimate. Further, more than 95% of the wind power potential is distributed in just five states in southern and western India—Tamil Nadu, Andhra Pradesh, Karnataka, Maharashtra, and Gujarat. The state of Karnataka has the largest wind resource potential (655 GW at 80 m), while Tamil Nadu has the largest best-quality wind resource (i.e., WPD >400 W $\mathrm{m^{-2}}$; CF $>32\%$) of 65 GW at 80 m. Thus it is seen that if all the Tamil Nadu's best-quality wind resoruces is fully utilized, wind power potential in the state alone would be 65 GW at 80 m hub-height and a minimum capacity factor of 32%.

From the findings of the above three studies, it could be concluded that India's wind power potential is much larger than the official estimation of CWET. Realizing the need for reassessment, recently CWET also has decided to reassess India's wind power potential at 100 m hub heights using GIS based information [55].

5. Conclusion

Amongst the renewable energy options wind power has been identified as the most prospective alternative for future energy mix. The confidence on wind power can be realized from the recent growth of wind power at global level. Several countries have set specific target to meet substantial portion of their domestic energy demand from wind while many others have initiated large scale R&D. However, the installed wind power is still far below the potential estimates, both at global and regional context. This paper aimed to analyze the present status of wind power at global and regional level with a focus on major wind domanitaing regions. China, USA, Germany, Spain and India which

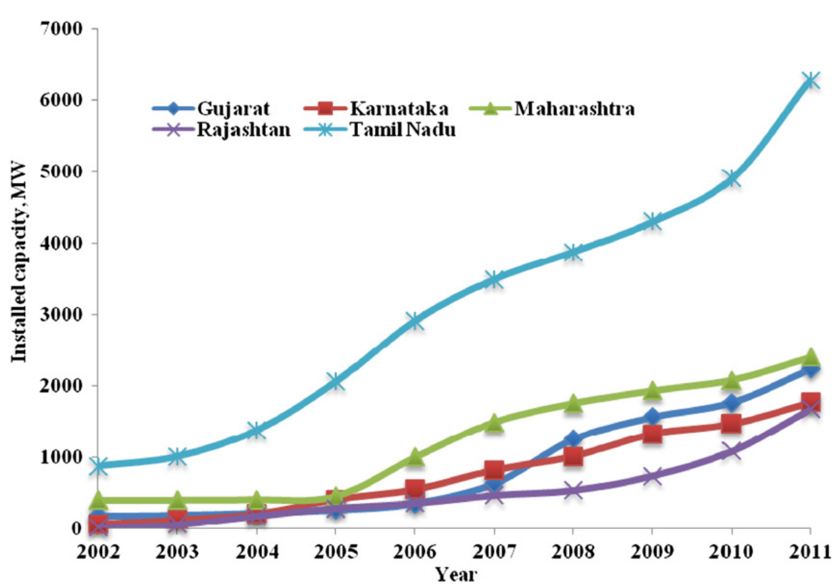

Fig. 9. Wind power installation status in the top five wind power producing states of India during 2002–2011.

altogether contribute about 74% of the total global installed capacity have distinctive local dynamics of wind growth rate. The accelerated growth rate of Chinese wind power installation, particularly beyond 2008, could be attributed to its favourable policy coupled with resource and technology support. It is also seen that to stimulate further growth of wind power, confidence on estimated potential need to be further enhanced. There has been some occasions where wind power potential have been reassessed at higher level. For example, the potential for India has been reassessed and found to be many times higher than previous estimate. The uses of modern tool and technique for assessment could lead to realistic assessement of actual potential. India's diversified growth of wind power amongst the states might have attributed to prevailing policies.

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